

# *Assessing the reliability of probabilistic flood inundation model predictions*

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1 Assessing the reliability of probabilistic flood  
2 inundation model predictions of the 2009  
3 Cockermouth, UK

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7 **Abstract**

8 An ability to quantify the reliability of probabilistic flood inundation  
9 predictions is a requirement not only for guiding model development but  
10 also for their successful application. Probabilistic flood inundation predic-  
11 tions are usually produced by choosing a method of weighting the model  
12 parameter space, but this choice leads to clear differences in the prediction  
13 and therefore requires evaluation. However, a lack of an adequate number  
14 of observations of flood inundation for a catchment limits the application  
15 of conventional methods of evaluating predictive reliability. Consequently,  
16 attempts have been made to assess the reliability of probabilistic predictions  
17 using multiple observations from a single flood event.

18 Here, a LISFLOOD-FP hydraulic model of an extreme ( $>1$  in 1000 year)  
19 flood event in Cockermouth, UK is constructed and calibrated using multi-  
20 ple performance measures from both peak flood wrack mark data and aerial  
21 photography captured post-peak. These measures are used in weighting the  
22 parameter space to produce multiple probabilistic predictions for the event.  
23 Two methods of assessing the reliability of these probabilistic predictions  
24 using limited observations are utilised; an existing method assessing the

binary pattern of flooding, and a method developed in this paper to assess predictions of water surface elevation. This study finds that the water surface elevation method has both a better diagnostic and discriminatory ability, but this result is likely to be sensitive to the unknown uncertainties in the upstream boundary condition.

## 1 Introduction and Objectives

Broadly speaking, there are two different philosophies to uncertainty estimation in flood inundation (hydraulic) modelling; these are Bayesian approaches that use formal likelihood measures, and the Generalized Likelihood Uncertainty Estimation (GLUE) methodology, applied to hydrological predictions by Beven and Binley (1992) which uses pseudo-likelihood functions instead of formal likelihood functions.

The majority of flood inundation studies have used GLUE-based approaches (e.g. Romanowicz *et al.*, 1996; Romanowicz and Beven, 1998; Aronica *et al.*, 1998, 2002; Romanowicz and Beven, 2003; Bates *et al.*, 2004; Werner *et al.*, 2005; Horritt, 2006; Pappenberger *et al.*, 2007a,b; Schumann *et al.*, 2008; Di Baldassarre *et al.*, 2009b), although some studies have adopted Bayesian approaches, (see Romanowicz *et al.*, 1996; Hall *et al.*, 2011). These studies have addressed one or more of the types of the uncertainty in the modelling; model structural choice (e.g. Apel *et al.*, 2009), model friction and conveyance parameters (e.g. Aronica *et al.*, 1998; Romanowicz and Beven, 2003; Bates *et al.*, 2004; Werner *et al.*, 2005; Pappenberger *et al.*, 2007a), boundary conditions (e.g. Pappenberger *et al.*, 2006, 2007a), and the geometry of the floodplain (Werner *et al.*, 2005) and channel (e.g. Pappenberger *et al.*, 2006, 2007a) (including the representation of natural and man-made flow control structures such as vegetation and buildings (Beven *et al.*, 2012)), as well as the observed data used to condition the models (e.g. Pappenberger *et al.*, 2007a; Di Baldassarre *et al.*, 2009b).

The dominance of GLUE-based approaches perhaps reflects an acceptance of the ‘effective’ nature of the parameter values used in most inundation models; sub grid scale processes as well as unrepresented boundary condition and structural uncertainties are lumped into the parameterisation. It is usual that conditioning of model parameters on observed inundation data is used to produce uncertain predictions (e.g. Romanowicz and Beven, 2003; Pappenberger *et al.*, 2007b,a; Mason *et al.*, 2009, (among others)), with various pseudo-likelihood functions in use to weight the model parameters based on their agreement with these observed data.

In Stephens *et al.* (2012) a LISFLOOD-FP hydraulic model of the River Dee, UK was calibrated and uncertain flood inundation maps were produced using different performance measures to weight each parameter set. It was shown that

the choice of performance measure for weighting the parameter space leads to differences in the final uncertain flood inundation map, with there being clear differences between a new uncertain measure (that implicitly takes into account the uncertainty in the observed water surface elevations), the RMSE and the Measure of Fit (Critical Success Index) used in studies such as that of Aronica *et al.* (2002). In this study the Measure of Fit will be referred to as the Critical Success Index as recommended by Stephens *et al.* (2014) to keep the terminology consistent with other disciplines.

Given the clear differences between uncertain flood inundation maps depending on how they are produced, there is a clear requirement for improving the ability to assess and quantify their reliability. This paper therefore focusses on the evaluation of uncertain flood inundation maps. In particular, two different methods are used to evaluate their reliability; the first method is that of Horritt (2006), and the second method is developed to account for the reliability of water surface elevation predictions (rather than the probability of a grid cell being wet / dry). Using these two different methods the reliability of the uncertain flood inundation maps and water surface elevation predictions produced using different methods of weighting the parameter sets is evaluated.

In this study the 2009 Cockermouth flood event on the River Derwent, UK is used as a case study. This allows for the method developed by Stephens *et al.* (2012), and the associated conclusions, to be tested on a different catchment, and is also a data-rich case study with a high spatial resolution (0.15m) aerial photography image that shows both the flood extent at the time of the photograph and enables identification of wrack marks to indicate water levels at peak flood.

## 1.1 Current methods for probabilistic evaluation of probabilistic flood inundation models

As Horritt (2006) notes, evaluation of a deterministic model prediction using data from a single event should be relatively straight forward (assuming any observed data of the flood to be perfect or the error distribution to be well constrained), but evaluation of uncertain model predictions is more problematic. Probabilistic evaluation of weather models is commonplace since ensemble forecasts have been used routinely since 1993 (NRC, 2006). This evaluation is largely enabled by a wealth of data as, for example, predictions of weather are made and realised on a daily basis. However, floods are rare events and consequently evaluating uncertain flood inundation model predictions using a (very) limited number of observations is problematic (Horritt, 2006).

Despite this, it is important for the applicability of probabilistic predictions to be able to state their accuracy: does an 80% chance mean that the event occurs

101 80% of the time? Therefore, even if the requirements of the formal probabilistic  
102 evaluation methods used in fields such as meteorology cannot be met because of  
103 data limitations, attempts should be made to evaluate probabilistic predictions  
104 using the few data that are available. Accordingly, modellers of extreme events  
105 and climate change, who have similar data limitation issues, have proposed the  
106 use of spatial patterns of predictions and outcomes to build sufficient datasets for  
107 evaluation (Horritt, 2006; Annan and Hargreaves, 2010).

108 Horritt (2006) proposed a method to validate inundation model predictions us-  
109 ing a single observation of flood extent (hereby referred to as the Horritt method),  
110 in effect, aggregating observations of the flooded state within each grid cell to  
111 produce a large enough sample size. A LISFLOOD-FP model (Bates and De Roo,  
112 2000) of a reach of the River Severn was set-up, and calibration / validation data  
113 were provided by two SAR images of flood events in October 1998 and Novem-  
114 ber 2000. The model was calibrated using one dataset, and validated using the  
115 other, therefore allowing for some independence between model calibration and  
116 evaluation.

117 Horritt (2006) proposed that uncertain flood maps produced using multiple  
118 simulations that are weighted using different model parameter sets should be clas-  
119 sified into regions of similar probability. By counting the number of observed wet  
120 cells in each of these regions it is possible to calculate reliability and visualise it  
121 using a reliability diagram. A perfectly reliable prediction would be one where,  
122 for a region of cells of similar inundation probability, the percentage of wet cells in  
123 this region is equal (or similar) to that probability. For example, if 15% of cells in  
124 the region characterised by 10-20% inundation probability are observed as flooded  
125 then this prediction could be considered reliable. The reliability can therefore be  
126 calculated as an average of the differences between the average forecast / predicted  
127 probability and the observed probability, and would take a value of 0 for a perfectly  
128 reliable forecast.

129 Although the Horritt (2006) paper maintains separation between the cali-  
130 bration and validation data, the Horritt method does not account for the co-  
131 dependence between the observations used in the analysis. For example, it is  
132 likely that if one cell on the floodplain has a predicted inundation probability of  
133 50% and it is observed as being flooded, that any adjacent cells will have similar  
134 probabilities and observations. While Horritt (2006) suggests that the issue of  
135 only having single observations has been ‘neatly sidestepped’, it could be argued  
136 that by using observations from the same event on the same model domain leads  
137 to issues of co-dependence that could potentially bias the analysis.

138 To increase independence of observations it would be necessary to choose a  
139 subset of cells across the domain that are not related, and given a large enough  
140 number of cells this would be possible. However, a perhaps more sensitive and dis-

criminatory measure might be to evaluate the water surface elevation predictions themselves, looking at where the observations fall within the predicted distribution of water depths. Unlike the Horritt method, a method that used observations of water surface elevations as the evaluation dataset would not require a continuous flood extent to be recorded, and therefore could be applied where there are discontinuous measurements such as wrack lines, or where the continuity of flood outlines derived from remote sensing is limited due to dense vegetation disguising the true flood edge in particular areas.

As well as using more ‘independent’ observations and being applicable for a larger variety of data sources, it is hypothesised that a method that evaluates probabilistic water surface elevation predictions will be more sensitive and therefore allow for better discrimination between the performance of different uncertain flood predictions. To judge this, different performance measures are used to weight water surface elevation predictions and produce predicted water elevation distributions for points across the domain. The objectives of this paper are therefore as follows:

1. To evaluate, for the 2009 flood event in Cockermouth, what performance measure / weighting method produces the more reliable probabilistic flood inundation predictions
2. To confirm the consistency of this conclusion by comparing results for calibrating / evaluating at time of peak flood and for the time of aerial photography overpass during flood recession, again using the Cockermouth dataset.
3. To compare the method for evaluating probabilistic predictions that is developed in this paper with the Horritt method, determining whether they produce the same outcomes, and which is more sensitive and therefore better for discriminating between these different weighting methods
4. To determine what can be learnt about the model from the two different methods for evaluating probabilistic predictions

## 2 Methodology

### 2.1 Study site and test data

The study site for this paper is the River Derwent in Cumbria, in the north-west of England (see Figure 1). The River Derwent flows west from Bassenthwaite Lake towards Cockermouth, where it meets the River Cocker and then continues on its westerly path to join the Irish Sea at Workington (see Figure 2).

175 An extremely large flood event occurred in the catchment in November 2009  
 176 after a prolonged period of rainfall over the mountains of the central Lake District.  
 177 At the Seathwaite Farm raingauge in the upper reaches of the Derwent catchment a  
 178 new UK record 24-hour rainfall record of 316.4mm was established for the 24-hour  
 179 period up to 00:00 on the 20th November, and estimated to have a return period  
 180 of 1862 years (Miller *et al.*, 2013). Due to the prolonged period of rainfall (10mm  
 181 / hour average for 36 hours) (Miller *et al.*, 2013), levels of major lakes within the  
 182 region reached new recorded maxima and consequently their buffering effect on  
 183 downstream flows was reduced (Miller *et al.*, 2013). Using an improved Flood  
 184 Estimation Handbook flood frequency analysis Miller *et al.* (2013) estimate that  
 185 the discharge return period on the Derwent at Ouse Bridge was 1386 years, and  
 186 769 years on the Cocker at Southwaite Bridge. The combined flow at Camerton,  
 187 estimated by the Environment Agency (EA) as  $700m^3s^{-1}$  has a return period of  
 188 2102 years, with 95% confidence limits of 507 and 17706 years (Miller *et al.*, 2013).

189 The re-evaluation of return periods following the flood has led to increases in  
 190 the estimates of the 1 in 100 year (21% increase) and 1 in 1000 year (38% increase)  
 191 flows used to produce deterministic flood inundation maps for the Environment  
 192 Agency, and subsequently used for planning purposes.

193 Gauged flow data (see Figure 3) are available for this flood event from Ouse  
 194 Bridge on the Derwent (the outflow from Bassenthwaite lake), Southwaite Bridge  
 195 on the Cocker (upstream of Cockermouth), and Camerton which is approximately  
 196 6km downstream from the confluence of the Cocker and Derwent as the crow  
 197 flies. The flood is modelled from 12:00 on 17th November 2009, before water  
 198 levels begin to rise, to 23:45 on 23rd November 2011, where water levels are nearly  
 199 back to normal levels. Flow data for the River Marron have been provided by  
 200 Professor Sear of Southampton University, by rescaling the flows in the Cocker  
 201 using the comparative size of the catchments. For the Ouse Bridge gauge, the EA  
 202 has provided metadata to advise that the stage at the peak of the flood has been  
 203 edited using estimates of the maximum flood level from a wrack survey, with the  
 204 time of peak and the infilled data estimated using correlation techniques. Further,  
 205 for the conversion to flow data using a rating curve the Quality flag is given as  
 206 ‘Estimated’ and ‘Extrapolated Upper Part’. For the Southwaite gauge, the stage  
 207 data is assigned a quality of ‘Good’ throughout, with approximately 17 hours at  
 208 the peak of the flood where the information has been edited to use the back up  
 209 data from the gauge due to float and weight issues that caused slight differences in  
 210 the hydrograph. Accordingly, the Quality flag of the flow data is given as ‘Good’  
 211 throughout, and within the range of the rating curve for all but the 30 hours  
 212 around the peak flood, where the data has been extrapolated.

213 The Camerton gauge was severely damaged during the event, with ‘Good’  
 214 readings only recorded up to 19th November 2009 at 20:30 (68.5 hours into the

215 modelled flood). After this, the only available data are through correlation with  
216 the Southwaite gauge. The EA metadata also suggests that the river channel  
217 became 18m wider at the site of the Camerton gauge, thereby rendering useless  
218 the rating curve that existed for the site. For this study we ignore the data from  
219 the Camerton gauge, but make use of the data from the other gauges. Although  
220 the metadata reports show that there are some quality issues with the flow record  
221 for this flood, these are typical for such a large event. Ideally the uncertainty in  
222 the gauged data should be accounted for, however, this was considered as outside  
223 the scope of this paper, which aims to develop methods for assessing reliability,  
224 addressing in particular the different methods of weighting the parameter space  
225 examined in Stephens *et al.* (2012). Significant further work is required to look  
226 at the data in more detail to examine how to place upper and lower limits on the  
227 uncertainty envelope for the rating curve for an event such as this with a flow of  
228 twice the size of the next largest flood event. The implications of this boundary  
229 condition uncertainty are considered when drawing conclusions from this study.

230 LiDAR elevation data at 2m resolution are available for the reach from the  
231 Ouse Bridge gauge to a few kilometres downstream of the former Camerton gauge  
232 (see Figure 2). The Digital Elevation Model (DEM) used in this study is an  
233 almagamation of data from flights in 1998 and April / May 2009, with the majority  
234 sourced from a dataset collected in 1998. LiDAR data of this resolution from 1998  
235 have a vertical Root Mean Square Error (RMSE) of approximately 0.25m (personal  
236 communication with Al Duncan, EA). The channel bed elevations have been burnt  
237 into the DEM using ground survey information from a 1D hydraulic model of the  
238 catchment provided by the EA.

239 Aerial photography of the flood is provided by the EA (see Figure 4 for an area  
240 of the image). According to the metadata provided the flight took place between  
241 13.10 and 14.50 on November 20th, so for the purpose of comparing to model  
242 results the time is taken as 14:00, (86 hours into the flood event as modelled).  
243 These data have a horizontal resolution of 15cm. An outline of a flood extent  
244 derived from the aerial photography was provided by the EA, and this was edited  
245 using the imagery as a reference to improve its precision, and then converted  
246 to points. This dataset of points has then been cut down by removing points  
247 which would likely be erroneous (such as at the boundary of, or underneath, dense  
248 vegetation), as well as next to walls or other vertical features where an accurate  
249 delineation of the elevation at the edge of the flood could not be achieved. This  
250 results in a total of 3724 data points. Well defined wrack marks are visible along  
251 much of the extent of the flood in the aerial photograph (see Figure 5). Manual  
252 digitisation of these marks has provided a total of 177 maximum water elevations,  
253 intersected with the LiDAR topographic data to provide maximum water surface  
254 elevations for further comparison with model results. The aerial photography data



will provide a stern test for the model on the falling limb of the flood. At the time of aerial photography overpass, flows still remained out of bank (as can be seen from the imagery), and so the floodplain is not considered to be draining at this point. However, it is worth noting that coarse resolution models have been shown to be poor at draining the floodplain (Bates *et al.*, 2006; Wright *et al.*, 2008; Neal *et al.*, 2011).

While in many studies aerial photography is used as a benchmark to assess the accuracy of satellite observed flood extents (Horritt *et al.*, 2001; Mason *et al.*, 2007), thereby assuming it to be accurate and precise, here this assumption is not made since these data will contain unknown errors. This is demonstrated in Figure 6, where there is obvious deviation from a smooth water surface for what should be an easy 200m stretch of floodplain to delineate the flood extent from. These deviations from a smooth water surface will be from two sources; the first being geolocational errors in the (manual or automatic) demarcation of the outline and the geocorrection of the data, and the second; errors in the LiDAR data used in the intersection of the flood extent and the topography. While it could be argued that the deviation would be smaller if the points were better digitised, these points have already been manually repositioned from the data as provided by the EA, and consequently any better recorection of these 2000+ data points would be a significant time burden. Also, and as can be seen in Figure 6, there is some confusion over whether the edge of the water surface lies at the edge of the sediment-laden area of water, or whether it lies at the edge of the surrounding darker area of vegetation which could be the current flood level, emergent vegetation or simply wet vegetation that has been previously flooded. Further, the vertical height errors that are incorporated with the intersection with the LiDAR data could be in the region of 0.25m RMSE, and cannot be removed.

## 2.2 Model Set-Up and Calibration

A 2D LISFLOOD-FP model was set-up using the inertial formulation of the shallow water equations as described by Bates *et al.* (2010). The model incorporates the LiDAR topographic data outlined above rescaled to 20m resolution to enable multiple simulations to be run without unreasonable computational cost, and the gauged data as upstream boundary conditions. The gauged data for Camerton have not been used as a downstream stage-varying boundary condition due to the known poor data quality. Instead a free boundary condition has been imposed using test runs of the model to approximate the water surface slope at this part of the catchment, which was shown to vary slightly from the local valley slope. The model is run for 167.75 hours, from 12.00 on 17th November 2009 to 23:45 on the 23rd November 2009, across a domain 100km<sup>2</sup> in size (including No Data cells). A simulation of the model run on 4 processors of the University of Bristol's Blue

Crystal supercomputer takes between 1.5 and 2 hours depending on the friction parameters used, and the model runs with very small mass balance error.

The upland nature of the upper Cockermouth catchment means that channel friction values might be higher than lowland rivers such as the Dee due to a gravel bed, and consequently, floodplain friction values may possibly be lower than those for the channel due to the pastoral land use which dominates the floodplain across the catchment. While it is expected that parameter values are effective, physically-based parameter ranges can be used to define the parameter space. According to Chow (1959) pasture with short grass would have a minimum Manning's  $n$  of 0.025, and a gravel bed would have a minimum of 0.030. Some areas of the catchment are heavily forested or have medium to dense brush, which might be expected to have a maximum Manning's  $n$  value of 0.12 (Chow, 1959). To ensure that the entire range of potential friction values are sampled, but also accepting that friction as specified in LISFLOOD-FP also acts as an 'effective' parameterisation (to account for unrepresented model structures such as sub-grid scale topographic features, and also unquantified uncertainties such channel topography and input flows), the parameter space is defined by channel and floodplain friction values of between 0.02 and 0.14. Calibration of the model was carried out by randomly sampling 300 parameter sets from the parameter space.

Four different measures are used to assess the performance of each of the three hundred parameter sets. The first is the water surface elevation comparison described by Mason *et al.* (2009), which is simply the Root Mean Square Error (RMSE) between the DEM elevation at each point on the observed flood margin, and the nearest water surface elevation in the model. If the cell that the observed point occupies is not flooded in the model, then an algorithm looks around adjacent cells (and then at cells of an increasing distance away) to this point until the water surface elevation is found. If multiple cells of an equal distance to the observed data point have a water surface elevation value then the value of the cell with the closest DEM elevation to the observed data point will be used. The second performance measure is the binary Critical Success Index (CSI):

$$CSI = \frac{A}{A + B + C} \quad (2.1)$$

Where  $A$  is the number of cells correctly predicted as flooded (wet in both observed and modelled image),  $B$  is the number of overpredicting cells (dry in observed but wet in modelled) and  $C$  is the number of underpredicting cells (wet in observed but dry in modelled).

The third performance measure, Perc.50 is the percentage as optimum measure detailed in Stephens *et al.* (2012), developed to provide an (implicit) representation of the uncertainty in the observed data into the calibration process. For this measure, ten thousand subsets of fifty points are taken from the observed dataset,

and the parameter set which produces the lowest RMSE for each subset is recorded. The frequency for which each parameter set occurs as the optimum is calculated, and converted into a percentage of the total number of subsets that have been evaluated.

The fourth performance measure, Perc\_1 is similar to the third, except that it uses subsets of 1, i.e. just individual data points, and then records the optimum parameter set for each of the individual points. Again, the frequency for which each parameter set occurs as the optimum is recorded, and turned into a percentage of the total number of subsets that have been evaluated. It was decided to additionally use this measure (compared to Stephens *et al.* (2012)), since by sampling each point it may be possible to implicitly account for the full range of observed data uncertainty, with no averaging over observation errors. For example, a single observed water surface elevation, will contain some unknown uncertainty due to LiDAR data errors and potentially geocorrection errors when intersecting the observed outline with the topographic data, but provided that enough data points are used, the LiDAR topographic errors and any geolocational errors will be accounted for by combining the results from all of these points to look at the effect of the uncertainty on the modelled parameter space. This assumes that the errors are random rather than systematic.

The Perc measures allow for areas of the parameter space to be rejected, thereby acting as a behavioural threshold. One criticism of this measure could be that a model could be rejected by using this measure even if its performance compared to an optimal model could not be differentiated from the [estimated] observational error. There is no averaging of the observation errors in Perc\_1, and so it provides an alternative approach to model rejection. To test whether it is this rejection criteria that influences reliability, or the measure itself, two more weighting methods are used based on a simple adjustment of the RMSE and CSI weightings. These RMSE\* and CSI\* inundation maps are constructed using a simple adjustment of the RMSE and CSI weightings by setting all weightings for the RMSE and CSI measures to 0 for parameter sets that are deemed non performing from the Perc\_1 measure.

Other studies have represented the uncertainty in observational data more explicitly; Pappenberger *et al.* (2007a) use a fuzzy map of flood extent and a global fuzzy performance measure, and Di Baldassarre *et al.* (2009b) produced a ‘possibility of inundation map’ by looking at how the model calibration varies when different methods of determining the flood outline from two different SAR images of a flood event are used. However, these existing studies have focussed on the uncertainty in the pattern of flood extent. Such contingency table based performance measures have been shown to be problematic for model calibration given their sensitivity to spatial variations in topographic gradient (Stephens *et al.*,

2014), as such, research efforts should focus on the use of water surface elevation observations instead. Some studies have used an explicit representation of the uncertainty in satellite-derived water surface elevations for predicting flood wave propagation using a 1D model (Di Baldassarre *et al.*, 2009a) and discharge (Neal *et al.*, 2009), but this has yet to be addressed for (2D model) predictions of the pattern of flood inundation.

There is certainly a requirement for future inundation modelling studies to address explicit representations of uncertainty in water surface elevation observations, and these should also be tested using assessments of reliability. This was considered to be outside the scope for this study, as it would require a considerable amount of discussion on how best to address the multiple sources of error in the observed data, such as the affect of wind on the deposition of wrack marks or on the reflectance of the water surface for SAR imagery, error due to LiDAR resampling or registration errors in remotely sensed imagery. Accordingly, this study focusses on the behaviour of the Perc measures in comparison to the Critical Success Index and RMSE.

### 2.3 Probability of inundation maps

The generalized likelihood uncertainty estimation (GLUE) technique of Beven and Binley (1992) has been extended to estimate spatially distributed uncertainty in models that are conditioned using the binary pattern of flooding extracted from satellite data (e.g. Romanowicz *et al.*, 1996; Aronica *et al.*, 1998, 2002; Romanowicz and Beven, 2003). An ensemble of the model is run with each ensemble member using a different parameter set. These ensemble members are weighted in a probabilistic assessment of flooding based on their ability to match an observed binary flood extent. While these earlier studies conditioned uncertain predictions based on the model’s ability to match the binary pattern of flooding, Mason *et al.* (2009) detailed how the weighting could also be based on a model’s ability to match a set of observed water surface elevations, and Stephens *et al.* (2012), extended this water surface elevation comparison to use multiple subsets of these observed data. This percentage as optimum performance measure converts easily to a weighting because it sums to a percentage.

For the RMSE and CSI measures, parameter sets are weighted based on how they perform on a sliding scale from the best performing parameter set (weighting=1) to the worst performing parameter set (weighting=0). For example:

$$Weighting = \frac{RMSE_p - RMSE_{min}}{RMSE_{max} - RMSE_{min}} \quad (2.2)$$

Using the GLUE procedure extended by Aronica *et al.* (2002) it is possible to calculate and then map the probability ( $P_i^{flood}$ ) that a given pixel is inundated.

$$P_i^{flood} = \frac{\sum_j f_{ij} W_j}{\sum_j W_j} \quad (2.3)$$

Where  $j$  is the number of model simulations,  $f$  is the flooded state of the pixel (1 = wet, 0 = dry) and  $W_j$  is the weighting given to each model simulation.

## 2.4 Methods for evaluation of probabilistic predictions

Stephens *et al.* (2012) showed how these different methods of calculating the  $P_i^{flood}$  in each cell led to clear differences in the uncertain flood inundation maps produced. Consequently it is important to be able to evaluate how the use of different weighting methods influences predictive skill. It is possible to carry out such an evaluation by assessing the reliability of model predictions. Detailed below are two different methods of evaluating the reliability of uncertain flood inundation maps used for this study.

### 2.4.1 Assessing reliability using the Horritt method

A reliability diagram allows for a visual assessment to be made of whether the model is over or underestimating probabilities, by plotting the predicted probability on the x-axis, and the observed probability on the y-axis. A perfectly reliable prediction would lie on the 1:1 line. The reliability can be quantified as an average of the differences between the average forecast / predicted probability and the observed probability (Stephenson *et al.*, 2008):

$$Reliability = \frac{1}{N} \sum_{k=1}^m n(\bar{f}_k - \bar{o}_k)^2 \quad (2.4)$$

Where  $\bar{f}_k$  is the mean of the probability forecasts of event  $k$  occurring (in each bin), and  $\bar{o}_k$  is the observation of event  $k$ .  $N$  is the total number of observations,  $n$  is the number of events that fall into each bin  $m$ . Such an evaluation of reliability requires a wealth of event data which is problematic given the (very) limited number of observations of flood inundation (Horritt, 2006).

Despite this, it is important for the demonstration of the applicability of probabilistic predictions to be able to give some estimate of their reliability. Accordingly, modellers of extreme events and climate change, who have similar data limitation issues, have proposed the use of spatial patterns of predictions and outcomes to build sufficient datasets for evaluation (Horritt, 2006; Annan and Hargreaves, 2010). As such, Horritt (2006) proposed assessing reliability using the probabilities of inundation assigned to each cell.

For the Horritt method Equation 2.4 is adjusted such that  $\bar{f}_k$  is the mean of the probability forecasts of a cell being flooded  $k$  (in each bin), and  $\bar{o}_k$  is the

439 observation of flooding  $k$  in each bin.  $N$  is the total number of observations,  $n$  is  
440 the number of events that fall into each bin  $m$ . Note that for the Horritt method  
441 model cells where the predicted probability of flooding = 0 are ignored in the  
442 calculation since they account for the vast majority of the domain and therefore  
443 would bias the result.

#### 444 2.4.2 Assessing reliability of water surface elevation predictions

445 To achieve an assessment of the reliability using water surface elevation predictions  
446 rather than the probability of inundation in each cell the following methodology  
447 is proposed:

448 The first step is to calculate a predicted water surface elevation probability  
449 distribution for each cell, based on a weighting using the performance measures  
450 used in Stephens *et al.* (2012). It is important to sample from a large parameter  
451 space so that the limits of the probability distribution are not predetermined by a  
452 subjective choice of potential parameter sets. For observations where the modelled  
453 water surface elevation is zero an algorithm is used to search, with a increasing  
454 distance away from the observation cell, for the nearest water surface elevation.  
455 Where two cells of equal distance away from the observation contain water, the  
456 water elevation value from the cell with the closest topographic elevation to the  
457 observation cell is used.

458 The next step is, for each observation, to record where it lies within the pre-  
459 dicted probability distribution. These records of observation location can be rep-  
460 resented in a cumulative frequency plot, where the number of observations that  
461 fall within each bin of predictions is plotted. If the predictions are perfectly re-  
462 liable the gradient of the line should be 1 since 10% of observations would fall  
463 within the first 10% of the probability distribution, 20% within the first 20%, and  
464 so on. Where the gradient is steeper than the 1:1 line then, in general, there has  
465 been an overestimation of the uncertainty in the model. Where the gradient is  
466 less steep than the 1:1 line there has been an underestimation of uncertainty, with  
467 observations having been made that lie outside of the predicted range.

468 An indication of bias within predictions, or where the full range of uncertainty  
469 has not been adequately captured, can be seen by identifying where the line inter-  
470 cepts with the vertical lines of  $x=0$  (the  $y$  axis) and  $x=100$ . The intercept with  
471 the  $y$  axis is the percentage of observations that fall outside the lower bounds of  
472 the predicted probability distribution of water surface elevations. The intercept  
473 with the line  $x=100$  can be subtracted from 100 to give the percentage of obser-  
474 vations that fall outside the upper bounds of the predicted probability distribution  
475 of water surface elevation predictions. The reliability of model predictions using  
476 this method can also be quantified using a calculation similar to Equation 2.4, by  
477 finding the difference between the expected and observed cumulative frequency of

478 observations 2.5. For the wse reliability the cumulative reliability is calculated  
 479 rather than an isolated comparison of the expected and actual number of observa-  
 480 tions in each bin to ensure that no model is penalised for bringing the probabilistic  
 481 predictions back towards the expected 1:1 line. For example, if no observations fell  
 482 within the first bin (0%-10% decile), then if 20% of observations fell in the (10%-  
 483 20% decile), then the first bin should be penalised for a 10% difference, but the  
 484 second bin should not be because it brings the overall percentage of observations  
 485 in the first two bins back to the expected value. As such, for the WSE method  $E_m$   
 486 is the expected number of observations to have fallen up to and including bin  $m$ ,  
 487 and the  $O_m$  is the actual number of observations to have fallen up to and including  
 488 bin  $m$ . If the bins were set as every 10%, then the total number of bins would be  
 489 10 and so the expected value for each individual bin inside the distribution would  
 490 be 10%.

$$Reliability = \frac{1}{N} \sum^m n(E_m - O_m)^2 \quad (2.5)$$

## 491 **3 Results**

### 492 **3.1 Modelled parameter space using different performance** 493 **measures / data sources**

494 Figure 8 shows the parameter space of the LISFLOOD-FP 2D model for different  
 495 performance measures using the aerial photography data. The Perc measures  
 496 provide well defined (perhaps spuriously precise) optimum friction values, whereas  
 497 the drop-off in performance across the parameter space is less defined for RMSE  
 498 and CSI. The RMSE measure (Plot a) and CSI (Plot b), show that these parameter  
 499 spaces are unexpected or at least unusual compared to those for other catchments  
 500 (such as the Dee), in that the model shows no real sensitivity to channel friction,  
 501 only floodplain friction. This sensitivity is also seen in the calibration using the  
 502 peak flood wrack mark data (Figure 9). This might be explained by putting this  
 503 particular flood event into context - the flows during this extreme event are so  
 504 large that the channel friction has little effect on the amount of water that flows  
 505 out of bank, and also in some areas the floodplain becomes the channel as flood  
 506 waters bypass river meanders. In effect, the entire valley floor is acting as a single  
 507 channel unit in conveying the large flows; the channel is only a small proportion  
 508 of the total flow area, and so floodplain friction is by far the dominant control on  
 509 flood extent.

510 Optimum friction parameter sets for each measure and each dataset are shown  
 511 in Table 1. For such an extreme event upstream boundary conditions are unlikely  
 512 to be error-free, and as described previously, the friction parameters used in the

modelling should also be considered as ‘effective’ given that they also compensate for subgrid scale processes. Accordingly, some deviation from physically realistic values for friction are to be expected, but a modeller that finds a ‘physically realistic’ parameterisation may have overconfidence in thinking that the model is robust with respect to other uncertainties. Here, the RMSE measure gives the most physically realistic floodplain friction optimum of around 0.03 for short pasture, the CSI measure finds higher than expected values, and the Perc measure does not find a well-defined optimum within the areas of the parameter space that might be considered to be physically realistic. However, it is important to assess whether these ‘physically realistic’ parameterisations produce reliable predictions.

It might be possible to conclude that there is no significant difference between the RMSE and CSI measures, given that the RMSE difference is less than the LiDAR data vertical error of 0.25m. However, care should be taken when drawing conclusions from averages of data. A histogram of the distribution of the two sets of model errors paints a more complete picture, giving an indication of the shift in the distribution of errors rather than just the difference between the means of each distribution. Figure 6 shows the error structure of two model parameter sets with RMSEs of 0.5624 (blue) and 0.4015 (red). It demonstrates that while the difference in RMSE is only 0.16m, a shift of approximately 0.4m would be required for the distributions to match, and this, backed up by the medians of each distribution (-0.0335 and 0.450083), is actually greater than the observed data error. Nevertheless, the observed data RMSE of 0.25m itself masks a distribution of errors, and therefore firm conclusions can not be drawn.

If a significant difference between the RMSE and CSI measures is assumed, it could be concluded that the CSI measure gives a much larger optimum value for floodplain friction than the other performance measures, while the broader pattern of non-sensitivity to channel friction remains the same. This comparison between parameter spaces can only be undertaken for the time of aerial photography overpass, since the CSI measure cannot be calculated for the discontinuous wrack marks dataset.

This optimum for higher floodplain friction parameters is investigated using a visual comparison between the observed dataset and the model output for two simulations with a fixed channel and different floodplain frictions (respectively of [0.027,0.026] and [0.027,0.057]). There are several areas across the domain where the higher floodplain friction simulation better matches a particular area of the observed extent than the low floodplain friction simulation (such as in the top right area of the catchment shown in Figure 10), but in doing so the higher floodplain friction simulation fails to match the areal pattern in nearby areas. These areas of unexpected inundation are not relics of observed data error, since there is strong agreement for multiple data points and they are clearly visible in the aerial



photography. This suggests that higher floodplain friction simulation is perhaps correctly matching the observed inundation in specific areas for the wrong reasons. There are several possible explanations for the inability of the lower floodplain friction simulation to capture these flooded areas; the model may have a resolution too coarse to accurately capture bank heights, or processes not represented in the lower friction model such as bank failure might be important. Consequently, it is thought that the higher floodplain friction simulation is matching the pattern of flooding better, but for the wrong reasons.

Stephens *et al.* (2012) and Stephens *et al.* (2014) described the CSI measure’s sensitivity to topographic slope, caused by it being more sensitive to correctly matching areas of the domain with low slope, where water elevation changes lead to greater changes in the areal pattern, rather than where gradients are steeper. Similarly, in this study calibration carried out using the CSI performance measure is more sensitive to (relatively) small parts of the model domain where there are large areal changes caused by tipping points (such as a bank being breached), than capturing the general pattern across the whole model domain. While for some applications it may be (more) important that the model correctly predicts these specific areas than the general pattern, caution should be exercised since the model could be capturing them for the wrong reasons or there could be observed data errors, therefore leading to a poorly calibrated model. While it is believed that for this case study the CSI might be showing the model matching the flood extent better but for the wrong reasons, it will be important to test this by evaluating the uncertain predictions produced when parameter sets are weighted using this and other performance measures.

In general there is more agreement in the form of the parameter space where the same performance measure is used for the two different datasets than between the measures themselves. This suggests that there is some consistency in parameter performance for two different times during the flood, but given that the interval between these datasets is relatively short, this consistency is less likely to occur for when flows are considerably different either during the same event or for different events.

The Perc\_1 and Perc\_50 plots distinguish areas of the parameter space that are non-performing, where parameter sets never appear as the optimum using multiple realisations of the observed data. Perc\_50 shows (as would be expected) larger non-performing areas than Perc\_1, since subsets of 50 act to average the range of uncertainty that can be represented using each individual point. The Perc measures hint that the optimum parameter sets sit to the margins of the parameter space, which suggests that the model (or at least its floodplain) contains too much water. This could be due to errors in the specification of the upstream flows, which is quite likely because of the potential errors in the gauged data detailed earlier in

593 this paper, or alternatively due to geomorphological changes during the flood event  
 594 that increased the capacity of the river channel. Such geomorphological changes  
 595 can be identified in a post-flood LiDAR dataset of the event, and consequently  
 596 will have some effect, although it is not possible without further modelling to be  
 597 confident of whether this or incorrect upstream flows are the cause of the apparent  
 598 bias in the model. Ignoring the CSI measure due to its known problems, it is inter-  
 599 esting that the RMSE shows a well defined optimum within the parameter space,  
 600 and this demonstrates the need for evaluating whether the Perc measures or the  
 601 RMSE provides more reliable predictions. As mentioned earlier in this study in  
 602 Section 2.4.2; it is important to ensure that the parameter space is large enough so  
 603 that the limits of the predicted probability distribution are not predetermined by  
 604 a subjective choice of potential parameter sets. The identification of optimum pa-  
 605 rameter sets at the margins of the parameter space for the Perc measures suggests  
 606 that this may be an issue; however the lower bounds for the roughness parameters  
 607 are limited by model stability rather than subjectivity, which is not untypical for  
 608 hydraulic models and is not thought to affect the conclusions drawn in this study.

## 609 **3.2 Uncertain Inundation Maps**

610 The Probability of Inundation maps shown in Figure 11 demonstrate the effect that  
 611 the choice of weighting method has on the mapping of flood hazard. Weighting  
 612 measures that act to discard areas of the parameter space as non-performing mean  
 613 that the flood margin becomes more certain / less blurred. This could lead to  
 614 spurious precision, or could be an effective way of determining which parameter  
 615 sets should be discarded or given low weighting: this can only be assessed by  
 616 looking at the reliability of the predictions.

## 617 **3.3 Reliability**

618 A reliability plot using the Horritt method is shown in Figure 12, and the associated  
 619 quantifications of this reliability can be found in Table 2. Note that the Horritt  
 620 method requires a binary flood map of wet / dry areas, so can only be carried  
 621 out using the aerial photography evaluation data since the wrack marks do not  
 622 provide a continuous boundary. Additionally, the reliability calculations for the  
 623 Horritt method are strongly influenced by the number of cells predicted as having  
 624 a 100% probability of flooding. Figure 12, Panel 2 does not use independent  
 625 calibration and validation data, so the analysis here is focussed on Panel 1.

626 Figure 12, Panel 1 (calibration using wrack marks deposited at the time of  
 627 peak flood) clearly demonstrates that the RMSE weighting overpredicts inundation  
 628 probabilities, and that the Perc<sub>50</sub> method is an improvement on the RMSE,  
 629 showing no bias but still some noise. As would be expected, the RMSE\* method

[0.0087] performs considerably better than RMSE [0.0161] since it uses the Perc\_1 method to discard non performing areas of the parameter space (parameter sets that never appeared as an optimum using multiple realisations of the observed data). Closest to the 1:1 line is the Perc\_1 method [0.0070], which shows little bias or noise. There is only one non-performing point for the Perc\_1 method that deviates far from the 1:1 line, and this could be due to the small number of data points in that category. Although drawing conclusions from Plot 2 should be done with caution because it uses the same dataset for calibration and validation data, it can clearly be seen that the CSI performance measure produces even less reliable predictions than RMSE.

The reliability plots using the new water surface elevation method are shown in Figure 13. In this Figure panels 1a) and 2b) use the same dataset for calibration and evaluation and so are not discussed. The WSE reliability plot for the time of flood peak (1b) reiterates the results of the Horritt method, showing that the CSI weighting produces the least reliable predictions, with RMSE also quite unreliable. These show that, on the whole, modelling using these weighting methods produces an overestimation of flood depths. The plotted line is always above the 1:1 line, showing that, in the case of CSI, 80% of observations fall within the first 20% of the predicted distribution of water depths. Discarding areas of the RMSE and CSI parameter spaces using Perc\_1 enables a small improvement in reliability (RMSE\* and CSI\*), but the overestimation of flood depths remains. The Perc\_50 method appears to have less bias than the RMSE or CSI, but should be penalised for the number of observations (approximately 20%) that fall outside the upper limit of the predicted range. The Perc\_1 appears to be the best weighting method since it lies close to the 1:1 line and no observations fall outside the upper limits of the predicted WSE distribution. This conclusion is solidified by the calculated reliability shown in Table 2, where Perc\_1 has clearly the best WSE reliability of 0.0133, and the RMSE\* (0.1072) and CSI\* (0.2120) measures do not perform better than even Perc\_50 (0.0254). Markedly, the CSI measure (0.3028) has a poorer WSE reliability than an equal weighting (0.2361) would provide.

The WSE reliability plot for the time of aerial photography (2a) in general shows that the model is less reliable after the flood peak (1b) than before it, and this is backed up by an approximate halving of the (best) reliability score for Perc\_1. It could also be argued that for the peak flood (1b) the model shows a tendency towards underpredicting flood depths (certainly for Perc\_1), whereas for the aerial photography (2a) there is definite overprediction. Previous studies such as Wright *et al.* (2008) have shown model accuracy to diminish after peak flood, and this result is repeated for the 2009 Cocker mouth event. The reliability plots used in this study suggest that the (effective) parameters used in LISFLOOD-FP modelling become less ‘effective’ post flood peak, in that they can no longer account

for as much of the uncertainty in the modelling post flood peak. Consequently it will be important to account for these uncertainties explicitly.

It is possible to compare the Horritt and WSE reliability methods by looking at the evaluation for the time of aerial photography overpass calibrated using the wrack marks dataset (Plot 1 of Figure 12 and Plot 2a of Figure 13). While it appears at first that the two plots are ‘switched’ in that the points in the former lie mostly to the bottom right side of the diagonal, and in the latter the points lie to the top left, actually the plots show the same pattern. The WSE reliability plots give an indication as to what percentage of the observations have fallen within the corresponding cumulative percentile of the predicted distribution. As such, while (for example) the RMSE calibration is shown for the Horritt reliability to be overpredicting the probability of inundation, the WSE reliability plot shows that more observations than expected have occurred for a particular predicted cumulative percentile; e.g. the model has overestimated the likelihood of higher water surface elevations. The WSE reliability plot also provides additional information to the Horritt reliability plots; demonstrating the percentage of observations that fall outside the predicted distribution of water surface elevations.

It is clear that Perc\_1 is the most reliable weighting method, but there is disagreement between the Horritt and WSE reliability methods over the worst performing weighting method. The WSE method suggests that it is Perc\_50, but the Horritt method identifies RMSE. This is because the Horritt method does not penalise observations falling outside the range of predictions: the Perc\_50 method for the time of aerial overpass shows only 60% to 70% of observations to fall within the predicted WSE distribution, and the line has a more shallow gradient than 1:1. The WSE method therefore makes clear that this Perc\_50 method underestimates the full range of uncertainty, probably because it has discarded too many parameter sets as non-performing. RMSE is again quite an unreliable measure (note that there is no CSI measure for this because of the calibration using the discontinuous wrack marks), but RMSE\* shows considerable improvement due to the link with the Perc\_1 measure.

## 4 Discussion

One of the aims of this paper was to evaluate the most reliable performance measure for weighting parameter sets to produce uncertain flood inundation maps. As well as the conventional performance measures of RMSE and CSI, the Perc measure, developed in Stephens *et al.* (2012), was also used to address how observed data errors are accounted for in the calibration process. Unlike the Perc\_50 measure, which uses multiple subsets of 50 data points, the Perc\_1 measure records, using individual observed data points, the number of times that each parameter set

appears as the optimum. This measure of agreement provides a parameter space that appears to give the best overall picture of the likelihood of each parameter set being the optimum.

Both methods of assessing model reliability show that the Perc\_1 measure produces the most reliable predictions, and this result is consistent for the validation data at the time of peak flood and at the time of the aerial photography overpass. This is a surprising result as, up until now, observations are usually grouped together into a ‘global’ dataset for model calibration. While Pappenberger *et al.* (2007b) highlight the importance of a vulnerability-weighted model calibration to produce an improved local model performance, e.g. with respect to locations of critical infrastructure, we show that considering observations individually can actually improve the global performance. But RMSE, as a measure which uses an average of all the (uncertain) observed data, will be influenced by outliers. As there is no reason to discard such an outlying point (unlike points that are in densely vegetated areas), there is still a (perhaps very small) chance that it is correct, and that all other points are affected by some systematic error. Therefore with these outliers influencing model calibration, it is important that they are used proportionately.

In the Perc\_1 measure an optimum parameter set that is only agreed upon by one data point will only be given a small weighting proportionate to the level of agreement, whereas for RMSE this data point will influence the characteristics of the entire parameter space. Perc\_1 therefore reduces the influence of what are likely to be erroneous data points, but gives them some weighting based on their agreement with the rest of the observed dataset, such that if 10 out of 1000 observations point at a particular optimum parameter set, this parameter set will be given a weighting of 1%.

It could be argued that the Perc\_1 measure should incorporate some kind of limits of acceptability approach so that a model is not rejected on this measure when its difference from an optimal model is less than the observational error. However, it is extremely rare to be able to adequately quantify the error in observations of flood extent, due not only to the availability of suitable validation datasets, but also because of the complexity of predicting the effect of wind on the deposition of wrack marks, or on the reflectance of the water surface for SAR imagery.

The Perc\_1 methodology implicitly accounts for the potential uncertainty, arguably providing a different approach to acceptability rather than applying a subjective behavioural threshold based on a simple estimation of observed data uncertainty for the limit of acceptability. If there were observed data of multiple flood events on a catchment, and none showed a particular parameter set as an optimum, then this parameter set would surely be rejected. The Perc\_1 measure

748 applies this logic (albeit with assumptions) to multiple observations from the same  
749 flood event; in this approach each observation is treated as a separate observation,  
750 such that if a parameter set is never the ‘optimum’ the agreement or lack of in the  
751 Perc.1 measure is used to define acceptability. Ideally, this of course requires that  
752 all sources of uncertainty are accounted for, as potentially areas of the parameter  
753 space might be discarded that would otherwise be acceptable, if, for example,  
754 boundary condition uncertainty were taken into account.

755 Assessing reliability is a good way of testing the methodologies for defining ac-  
756 ceptability and weighting the parameter space. In this study the focus was on the  
757 treatment of observed data for model calibration, and so the boundary condition  
758 uncertainty has not been taken into account. To provide a preliminary assessment  
759 of the sensitivity of the results described in this paper to upstream boundary con-  
760 dition uncertainty, a change in the hydrograph was simulated by taking / adding  
761 different amounts from the water surface elevations produced by the ensemble  
762 modelling Figure 14. These changes are commensurate with the changes seen  
763 when changing the hydrograph by a fixed percentage for a single parameter set,  
764 as indicated on the figure. The Brier reliability was recalculated for each applied  
765 change to give an indication of its sensitivity to boundary condition uncertainty.  
766 Figure 14 therefore demonstrates that if, in reality, the flows were consistently 10%  
767 lower then the choice of optimum weighting method would be different. Given that  
768 the uncertainty in the upstream boundary condition during this flood is unknown,  
769 this sensitivity urges caution when considering the robustness of these results.

770 Future work should explicitly incorporate boundary condition uncertainty into  
771 the analysis, as well as produce and test a methodology that incorporates a more  
772 detailed and explicit representation of observed data uncertainty, incorporating, for  
773 example, the resampling errors of the LiDAR data. Further studies are needed to  
774 confirm whether the conclusions are robust on different flood events with different  
775 magnitudes. Namely, does the Perc.1 measure produce the most reliable predic-  
776 tions for flood events of smaller magnitude, and can weighting using these smaller  
777 events still provide reliable inundation possibilities for extreme events such as the  
778 1 in 1000 year return period flood? Further, would a more explicit representation  
779 of uncertainty in the observed data produce more reliable predictions?

780 The other main aim of this study was to develop a new method for evaluating  
781 uncertain flood inundation predictions, and then compare the results from this  
782 with those from the Horritt method. One of the advantages of the WSE method  
783 is that it can be used for discontinuous datasets (such as the wrack marks in this  
784 study), and it therefore has wider applicability. On top of this, and despite both  
785 reliability methods coming to the same overall conclusion, there are differences in  
786 the level of information provided by each that indicates that the WSE method  
787 is more discriminatory, since it produces a wider range of reliability scores, and

also has wider diagnostic capabilities since it provides more information than the Horritt method. For example, the Horritt method does not show any bias when the Perc\_50 measure is used, but the plots of cumulative reliability for the WSE method clearly show that this measure underestimates the range of uncertainty in the model. This underestimation is caused by discarding areas of the parameter space as ‘non-performing’ when they should still be taken into account when producing the uncertain estimates of flood hazard. Further, the WSE method can show whether and how many of the water surface elevation observations lie within the predicted range. If they do not, then this hints at epistemic uncertainty that needs to be addressed.

The Horritt method is poor at telling the modeller of model underprediction, and this is especially the case for cells that had a predicted probability of flooding of 0. Depending on how the domain is set up, large proportions of the cells in it would have predicted inundation probabilities of 0, including cells that lie well outside or above the floodplain. If some of these cells did in reality flood then the flooded percentage would be biased by the sheer number of cells that have a predicted probability of 0, therefore the Horritt method does not quantify how wrong these predictions are.

Similar problems can be seen for overprediction of flooding. Cells that have a probability of inundation of 1 (or perhaps even 0.9 or greater), and that are observed as flooded, may have considerably greater water surface elevations than were predicted, but this would not be recognised or penalised. The WSE method is able to diagnose whether observations of water surface elevation fall outside the upper limit of the predicted distribution of water surface elevations. Further, it makes it possible to understand where the majority of observations lie within the predicted distribution.

Model evaluation using the WSE method has proved a useful diagnostic tool that provides more information about model performance than the Horritt method, giving an indication of the percentage of observations that fall outside the upper and lower limits of the probability distribution of water surface elevations. In the case of the Cockermouth flood it can be seen (using the Perc\_1 measure which has been identified as producing the most reliable predictions), that at the time of the peak flood the model has around 12% of observations that fall below the lower limits of the range of water surface elevation predictions, which increases to around 22% at the time of the aerial photography overpass. Despite there being no other study for comparison, that 88% of peak flood observations fall within the predicted range could be considered good for a model that only takes into account parameter and observed data uncertainty, and especially for such an extreme flood event where the errors in the inflow and wrack mark data are likely to be high. The drop in model performance only a few hours after peak flood suggests that

new sources of uncertainty need to be taken into account to produce a similar reliability to predictions made of the peak flood, and as mentioned previously the uncertainty in geomorphological change during the flood, or in the gauged flow data should be investigated.

Despite the apparent improvement in assessing reliability that the WSE method has over the Horritt method, this method is by no means a perfect test of probabilistic model performance. Such spatially-averaged approaches are problematic in that reliability is likely to be highly variable in space (Atger, 2003), and so an averaged estimate of reliability might hide local variations in model bias (Toth *et al.*, 2003). For example, the spatially-averaged reliability is likely to hide localised performance, for example, a perfect reliability might be recorded, but half of the domain might be overestimating probabilities and the other half underestimating them (Ferro, 2012). However, given the limited number of observations of flood inundation on a single catchment, the best that can be achieved is a careful analysis that requires a balance between achieving a sample size that is sufficient for a robust statistic, and being able to dissect localised variations in performance (Toth *et al.*, 2003).

## 5 Conclusions

This study aimed to determine which performance measure should be used to weight model parameter sets to produce reliable assessments of uncertain flood hazard. It was shown that the most reliable method is one that assesses the range in model performance across the parameter space by running multiple model calibrations using each of the observed data points individually. This result is in contradiction to current approaches used to map flood inundation, which generally group observed data points. However, an indicative assessment suggests that this conclusion may be sensitive to boundary condition uncertainty. Consequently it will be important to understand whether this conclusion is robust for flood events of different magnitude and in different locations.

This study has strong implications for the methodologies used for uncertain inundation mapping by practitioners; an uncertain treatment of observed data in the calibration process has been shown for the Cockermouth flood event to provide more reliable flood probabilities, and within or post-event surveyed water levels (where in abundance) are the best observed data to do this with because they will contain less uncertainty than water levels processed from remotely sensed extent data. In turn, these derived water levels have wider potential for use than binary maps of flood extent for model calibration and evaluation. It could be argued that these results reflect the better quality assurance carried out when processing extents to water levels, and to some extent this is true, but it is perhaps more



reflective of the ability of water elevation comparisons to make better or broader use of the available data.

In assessing these weighting methods a new method of evaluating the reliability of uncertain flood inundation predictions has been developed by recording where observations lie within predicted probabilistic water surface elevation distributions. This method not only has the advantage over existing methods of being applicable for observations that are discontinuous, such as wrack marks or remote sensing images in vegetated areas, but it is also a more discriminatory technique with better diagnostic capabilities. It gives an indication of whether uncertainty is being under or over estimated, whether there is bias in the model, and also calculates the percentage of water surface elevation observations that fall within the predicted range.

Consequently, this WSE method has provided useful information about the LISFLOOD-FP model of the Cockermouth flood event. It demonstrates that, at peak flood, 88% of water surface elevation observations fall within the predicted model range, suggesting that the model does not take into account the full range of uncertainty seen in the observations (assuming the observations to be error-free), and as the 12% of observations outside the predicted range lie outside the lower limits of the distribution, the model is clearly biased towards over-predicting flood depths, and the source of this bias should perhaps be further examined. As some of the water surface elevation observations will be erroneous (for example the wrack marks could have been laid down after the peak flood), perhaps this figure is within the limits of acceptability for these data, and therefore it could be said that the model is performing well, but it would be interesting to observe how this figure might change if a higher resolution model were used, or model results were resampled onto higher resolution topography.

This study also shows model performance decreasing over the course of the flood, suggesting that the uncertainties that are not accounted for have greater influence after the flood peak. Further research could aim to improve model reliability by taking into account the uncertainties introduced into the modelling by gauged flow errors and geomorphological change, and evaluate whether different model complexities can better represent these uncertainties. It could also address how the resolution of the topographic data used in the model influences reliability, and whether improving the resolution of topographic data limits the number of observations that fall outside the predicted range of water surface elevations. Further investigation could also examine the potential for using the Perc measure as a discriminatory tool to identify subtle differences between the performance of different model structures and the benefits of including explicit representations of different sources of uncertainty.

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Table 1: Optimum parameter sets of channel (ch) and floodplain (fp) friction identified using different performance measures for both aerial photography and wrack marks

Measure	Aerial Photography			Wrack Marks		
	ch	fp	Value	ch	fp	Value
CSI	0.026	0.057	83.67% (0.61m)	-	-	-
RMSE	0.038	0.029	0.40m	0.034	0.036	0.28m
Perc_50	0.054	0.022	12.42% (0.41m)	0.034	0.036	29.1% (0.28m)
Perc_1	0.047	0.02	20.76% (0.47m)	0.047	0.02	12.99% (0.48m)

Table 2: Brier Reliability for Different Uncertain Calibrations of the Cockermouth Model. Numbers in italics indicate where calibration / validation data are the same.

Weighting Method	Aerial Photography		Wrack Marks	
	Horritt	WSE	Horritt	WSE
Wrack RMSE	0.0157	0.038	-	<i>0.1304</i>
Wrack RMSE*	0.0079	0.053	-	<i>0.0279</i>
Wrack RMSE**	0.0133	0.128	-	<i>0.0255</i>
Wrack Perc_50	0.0157	0.1106	-	<i>0.0581</i>
Wrack Perc_1	0.0098	0.0221	-	<i>0.0130</i>
AP RMSE	<i>0.0157</i>	<i>0.0991</i>	-	0.1304
AP RMSE*	<i>0.0126</i>	<i>0.0460</i>	-	0.1072
AP RMSE**	<i>0.0115</i>	<i>0.2467</i>	-	0.0235
AP Perc_50	<i>0.0170</i>	<i>0.0435</i>	-	0.0254
AP Perc_1	<i>0.0087</i>	<i>0.0201</i>	-	0.0133
AP CSI	<i>0.0265</i>	<i>0.2467</i>	-	0.3028
AP CSI*	<i>0.0213</i>	<i>0.1998</i>	-	0.2120
Equal	<i>0.0268</i>	<i>0.2262</i>	-	0.2361

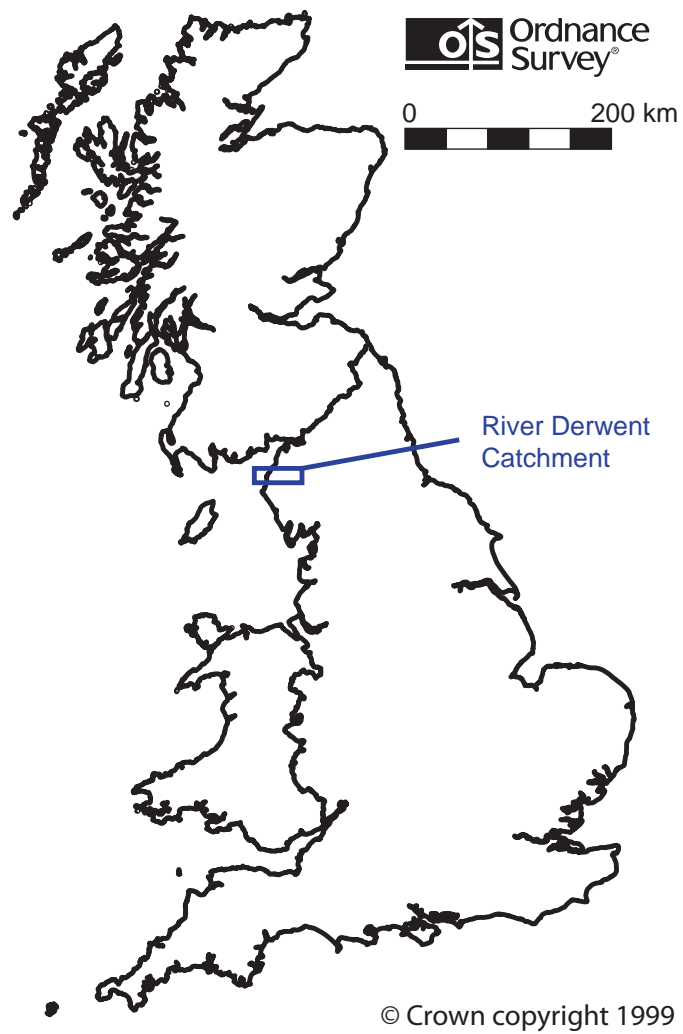


Figure 1: Location map showing the River Derwent catchment in the north-west of England. Source: Ordnance Survey

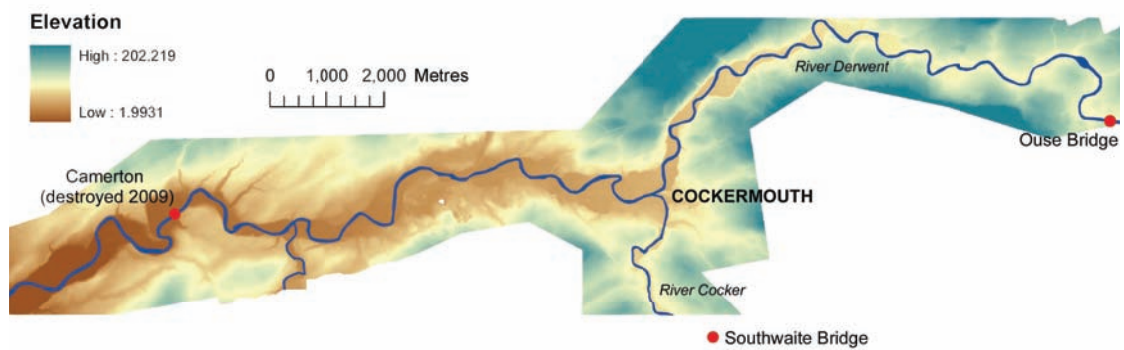


Figure 2: Topographic map of the River Derwent using LiDAR data at 2m resolution, showing location of gauges (red points). Source: Environment Agency

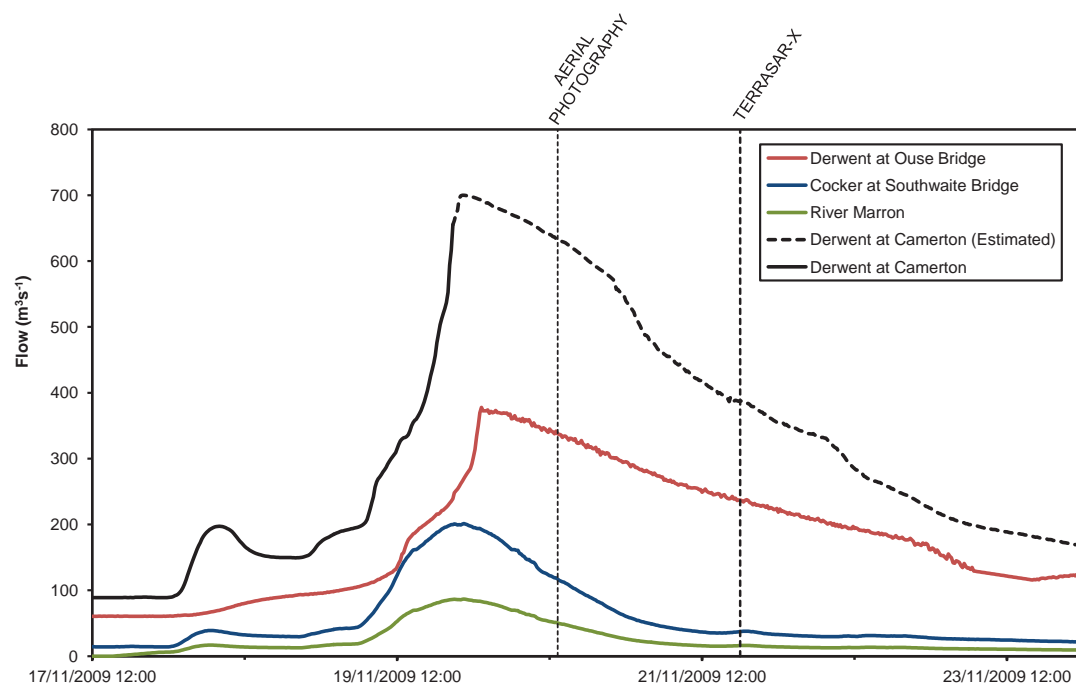


Figure 3: Gauged upstream flows for the River Derwent at Ouse Bridge, the River Cocker at Southwaite Bridge and the River Marron, with gauged downstream flows for the River Derwent at Camerton. Source: Environment Agency



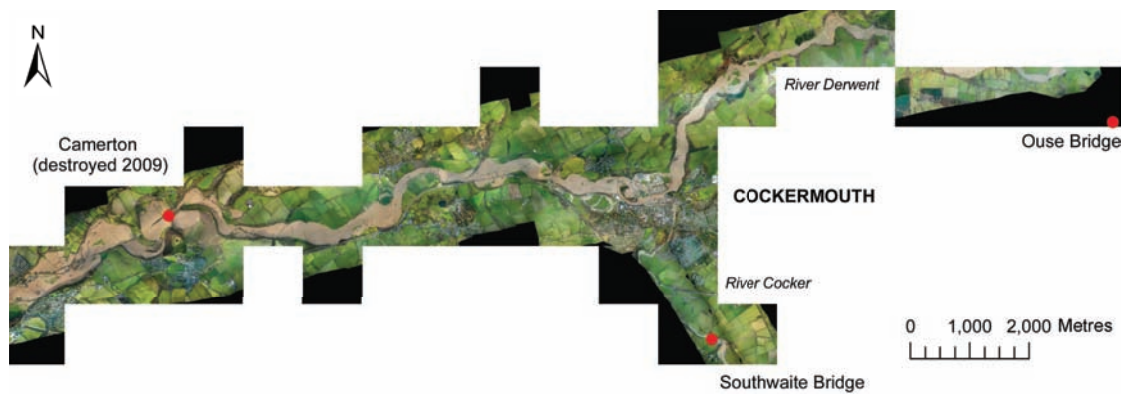


Figure 4: Extent of the aerial photography flown during the flood event. Source: Environment Agency

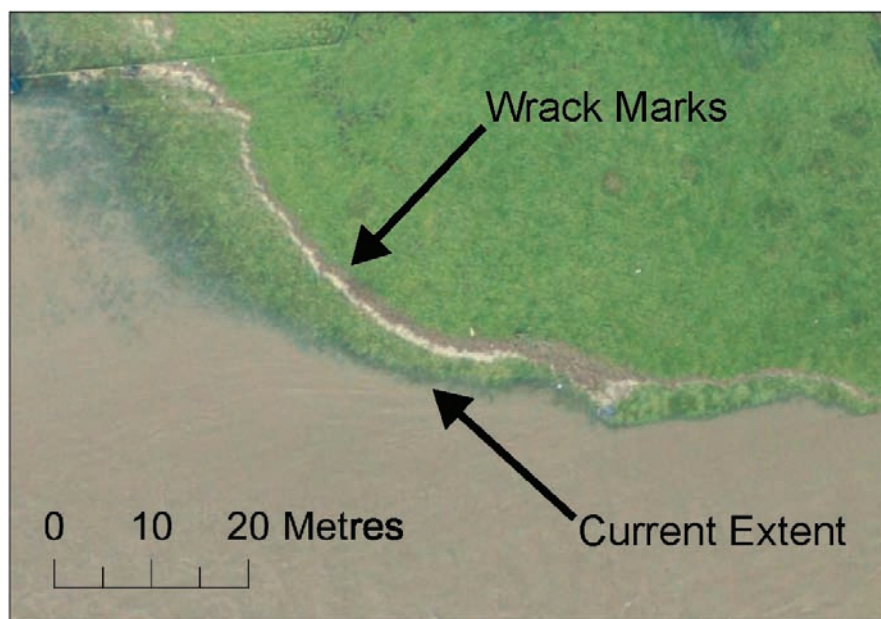


Figure 5: Example of wrack marks visible in the aerial photography adjacent to the then-current flood extent. Source: Environment Agency

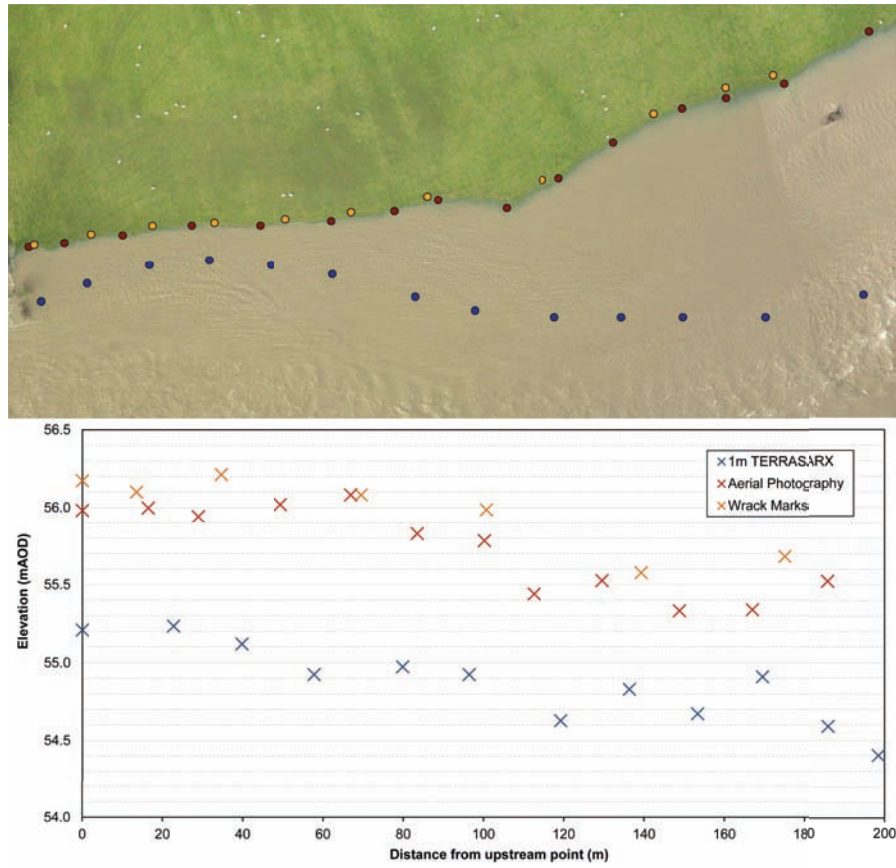


Figure 6: Demarked points along the margin of the flood along a field, with associated elevations derived by intersecting with LiDAR topographic data.

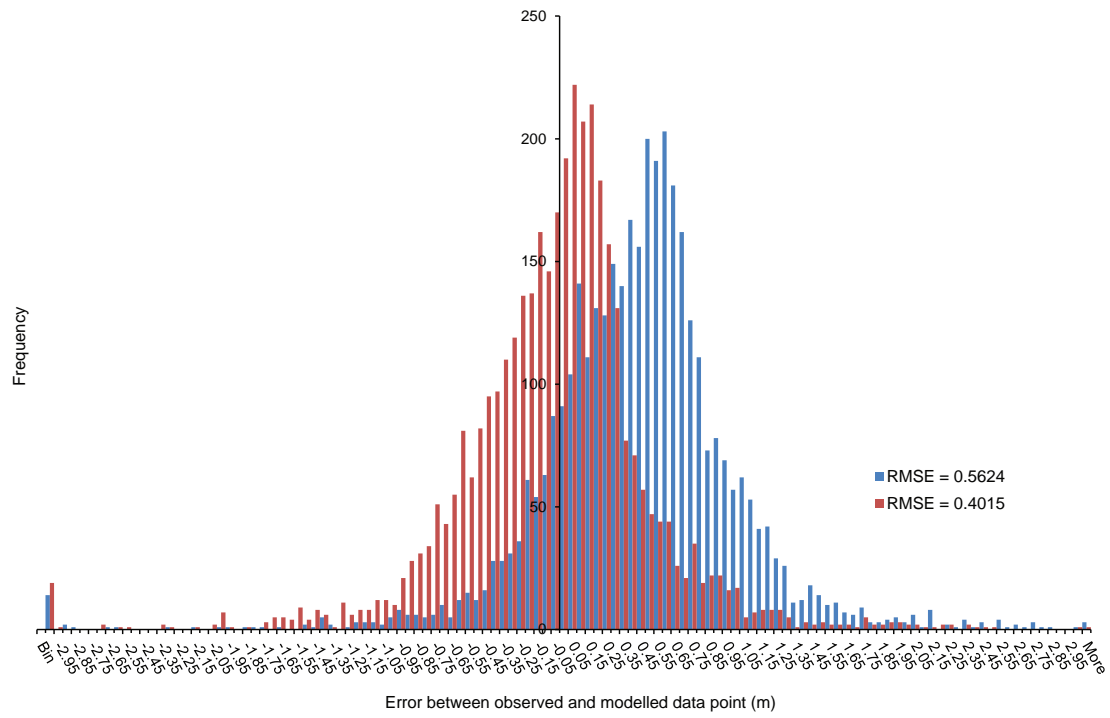


Figure 7: Frequency of error between individual observed and modelled data points, for two parameter sets with RMSEs of 0.5624 (blue) and 0.4015 (red).

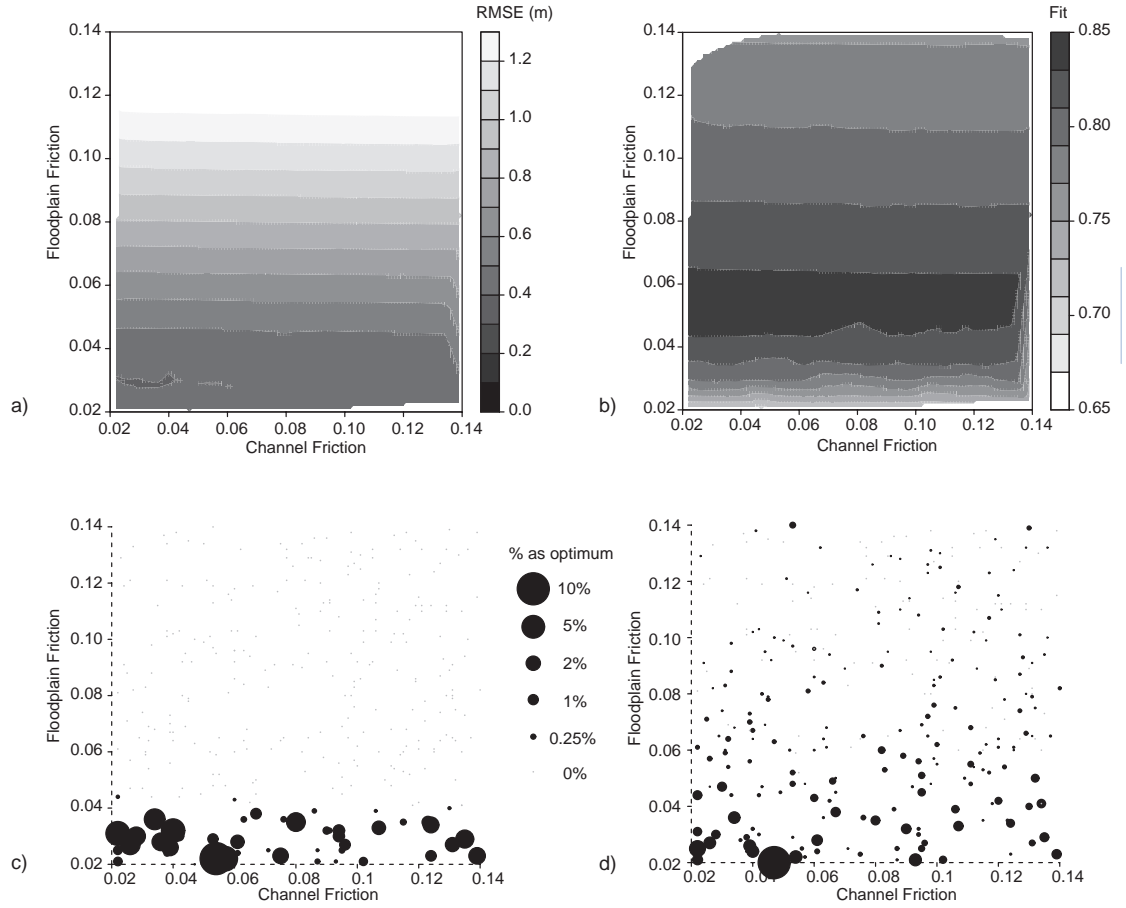


Figure 8: Parameter spaces for calibration of channel (x-axis) and floodplain (y-axis) friction parameters using Aerial Photography with the performance measures of: a) RMSE; b) CSI; c) Percentage as optimum parameter set for subsets of 50 points; and d) c) Percentage as optimum parameter set for all individual points (subsets of 1).

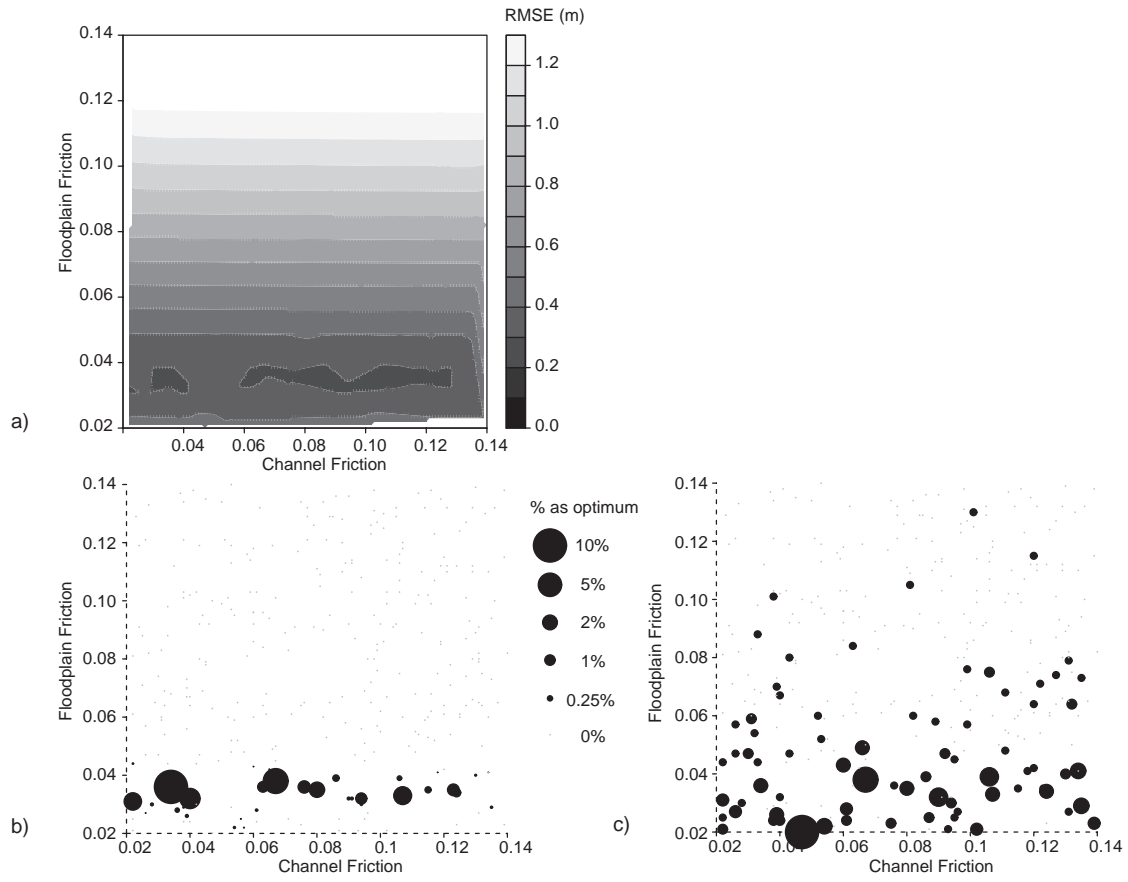
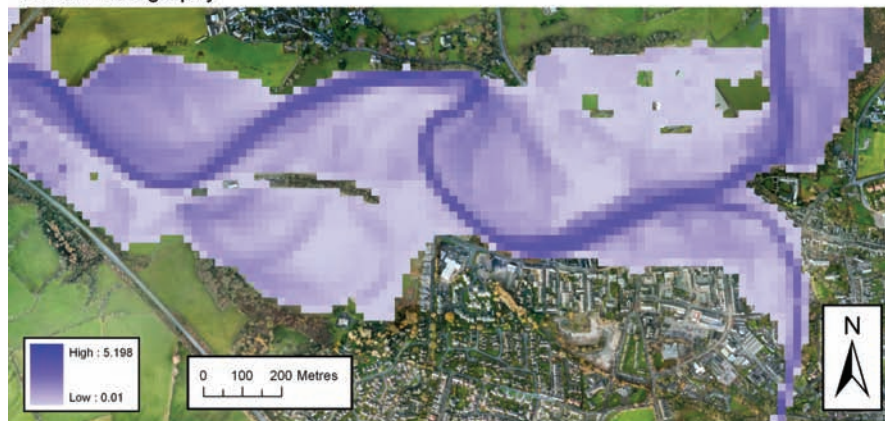


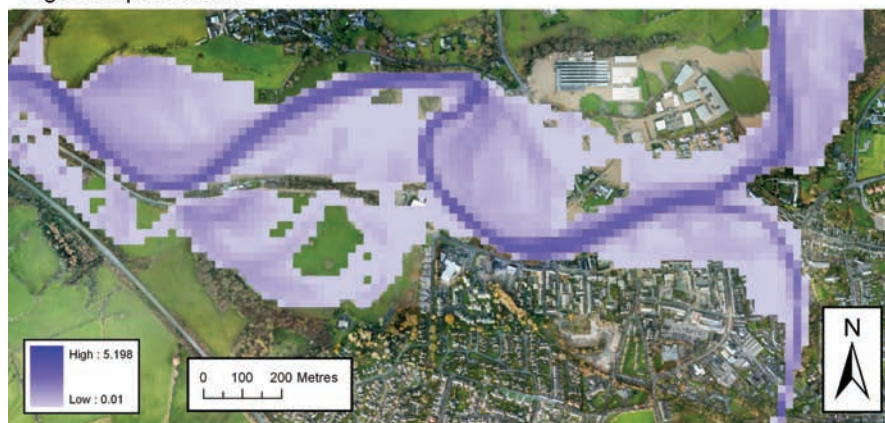
Figure 9: Parameter spaces for calibration of channel (x-axis) and floodplain (y-axis) friction parameters using Wrack Marks with the performance measures of a) RMSE; b) Percentage as optimum parameter sets for subsets of 50 points, and; c) Percentage as optimum parameter set for all individual points (subsets of 1).



Aerial Photography



High floodplain friction



Low floodplain friction

Figure 10: Difference in modelled extent compared to aerial photography for a high and low floodplain friction parameter sets on a subsection of the domain covering the Cockermouth area.



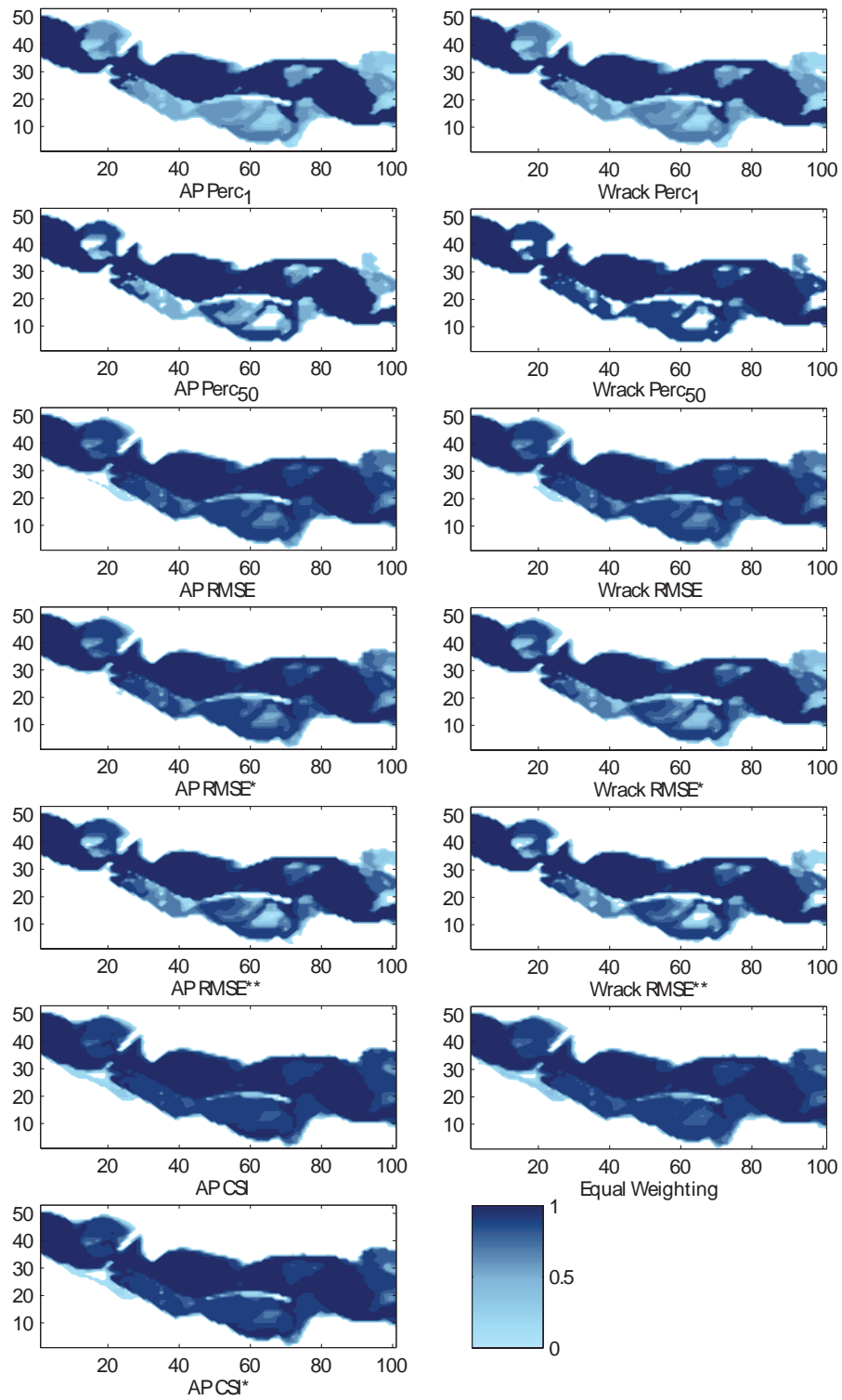


Figure 11: Cut-out from Probability of Inundation maps for the time of a Terrasar-X overpass (see 3). Showing the subtle differences in the mapped probabilities with the different weighting methods used for their construction.

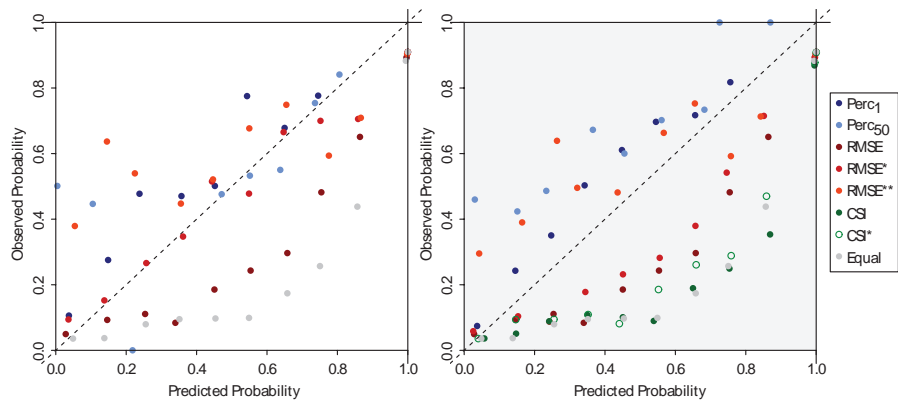


Figure 12: Horritt Reliability at the time of aerial photography overpass using calibrated weightings from 1) peak flood (wrack marks) and 2) aerial photography extent elevations. Greyed out plot indicates where the calibration / validation data are the same.



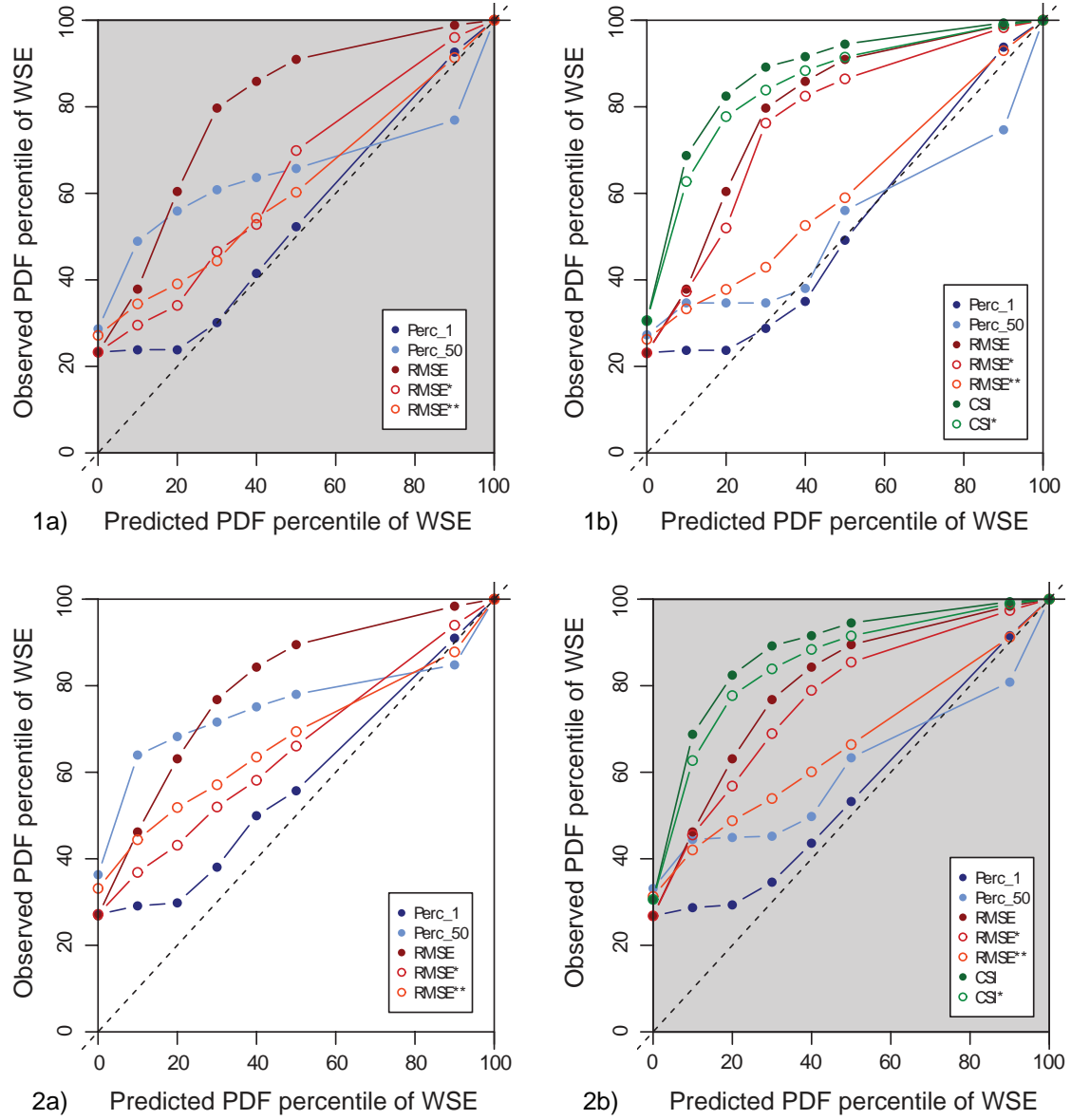


Figure 13: WSE Reliability for 1) Flood Peak using a) Wrack Marks, b) Aerial Photography, and 2) Time of Aerial Photography using a) Wrack Marks and b) Aerial Photography. Greyed out plots indicate where the calibration / validation data are the same

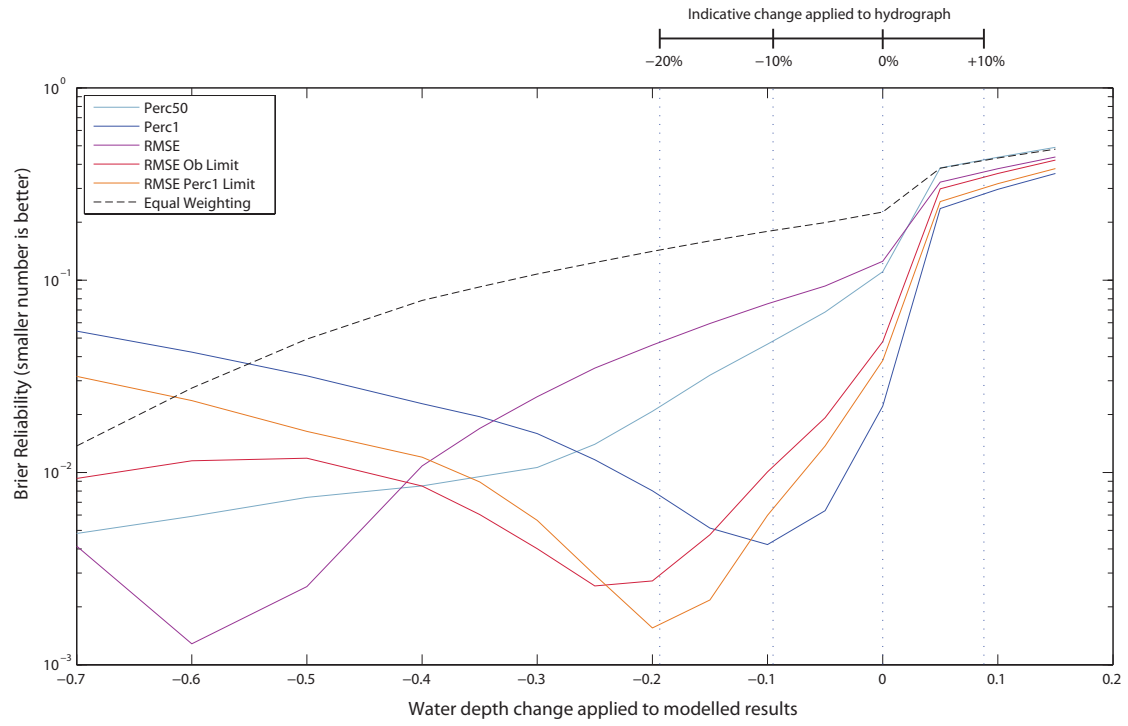


Figure 14: Change in Brier Reliability for different weighting methods if water depths are added / taken from the model results to represent boundary condition uncertainty. Bar along top gives indication of change in depths for different percentage change to flows.